

# Coupling at the ocean-atmosphere interface – boundary layer processes

CPO ESSM Workshop and Annual ESSM Council Meeting  
Silver Spring, MD  
Nov 7, 2018



**SOCCOM**  
Southern Ocean Carbon and Climate Observations and Modeling



Prof. Joellen L. Russell

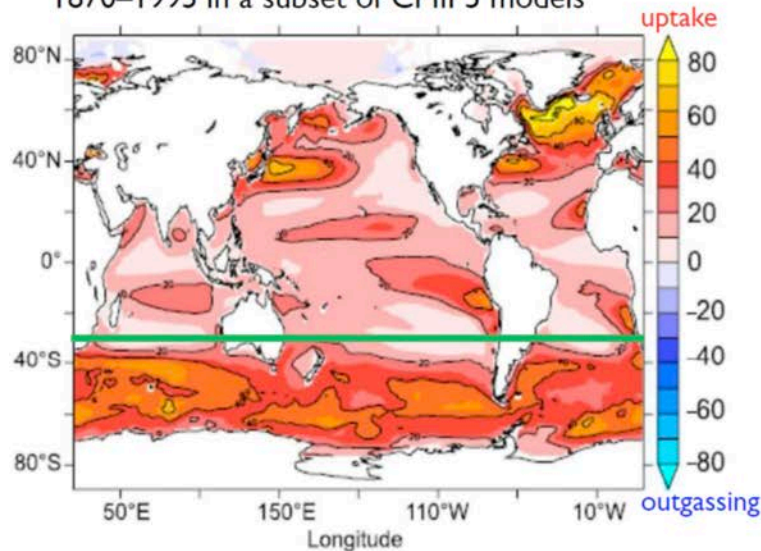
*Thomas R. Brown Distinguished Chair of Integrative Science  
Department of Geosciences  
University of Arizona*

# SOUTHERN OCEAN ROLE IN GLOBAL CARBON CYCLE

~30% of global surface ocean area

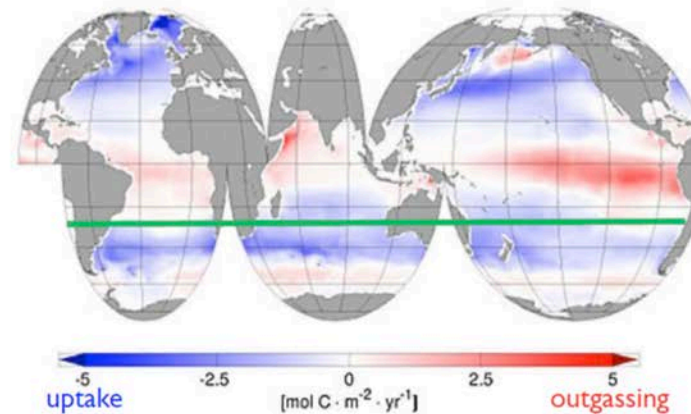
~50% of global oceanic uptake of anthropogenic CO<sub>2</sub>

Cumulative anthropogenic CO<sub>2</sub> uptake (mol m<sup>-2</sup>)  
1870–1995 in a subset of CMIP5 models



Frölicher et al. 2015

Mean 1982–2011 air-sea CO<sub>2</sub> flux (mol m<sup>-2</sup> yr<sup>-1</sup>)  
based on observations



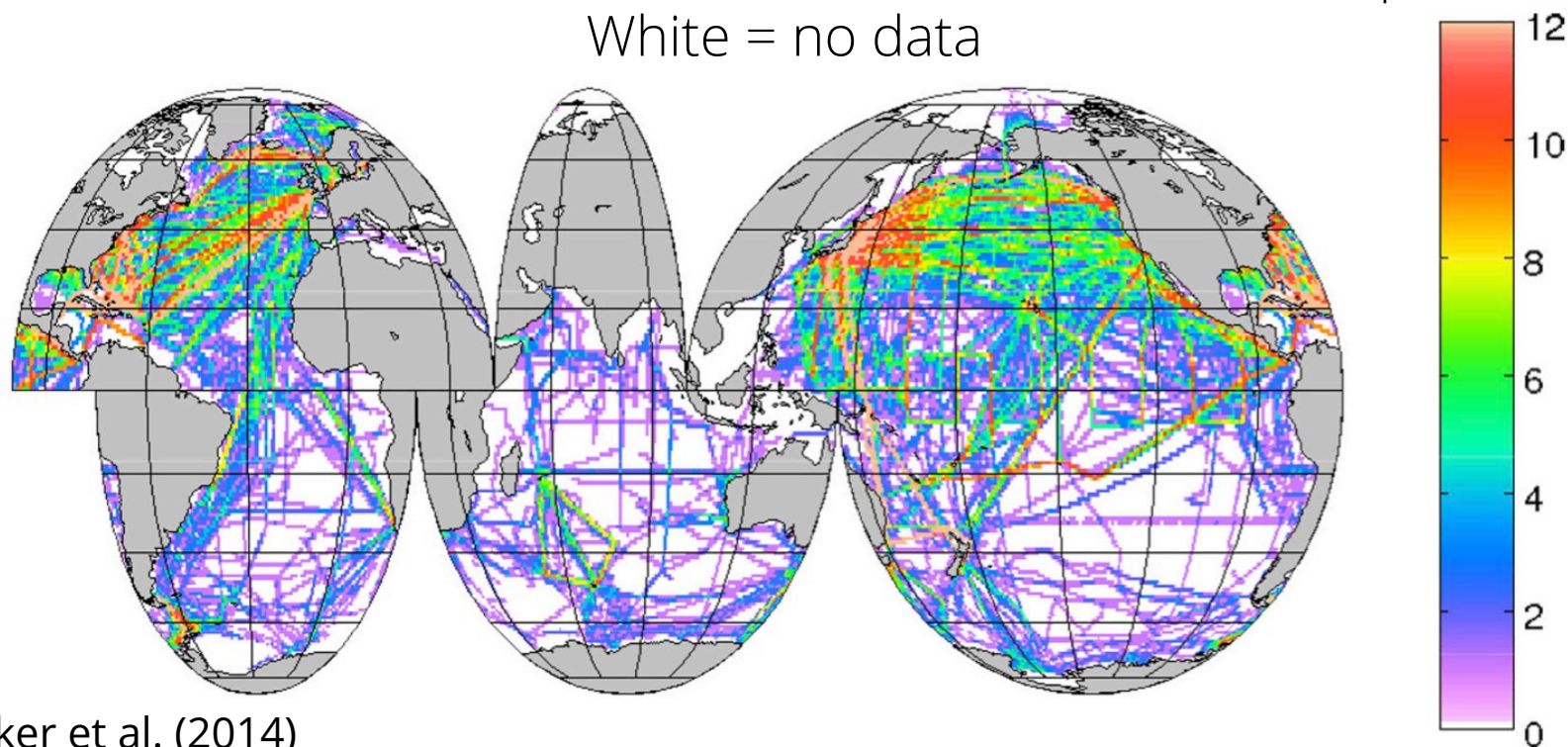
Landschützer et al. 2014

Courtesy – A. Gray

# Undersampling of $p\text{CO}_2$

Months of year with surface  $p\text{CO}_2$  measurements based on all measurements between 1970 to 2011 binned in  $1^\circ$  squares.

White = no data



Bakker et al. (2014)

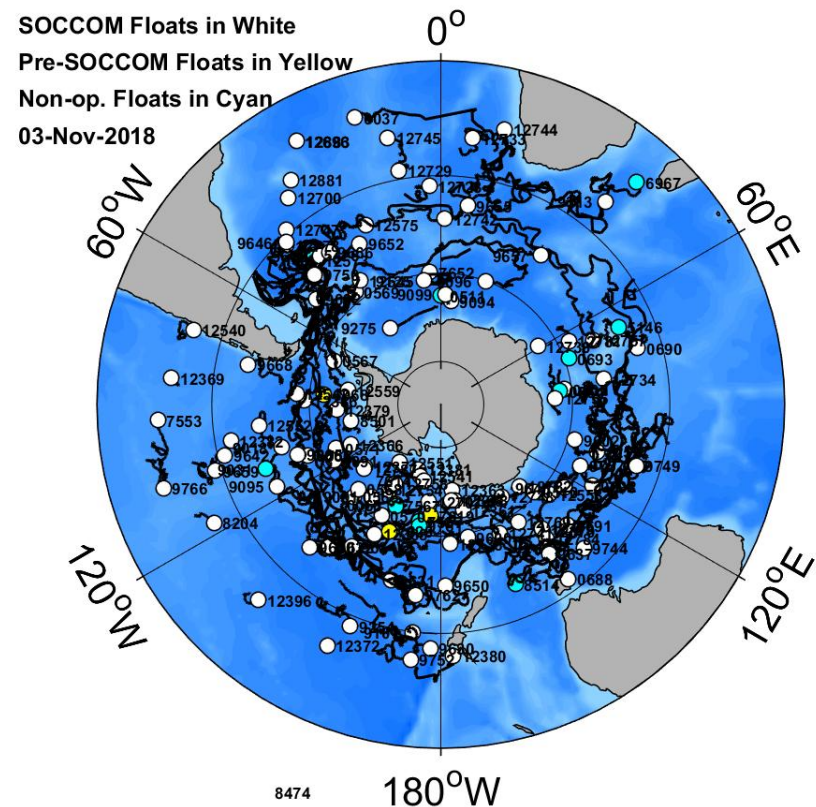
# Observations of the Southern Ocean

## New: Biogeochemical Profiling Floats (SOCCOM)



SOCCOM floats ○  
Pre-SOCCOM floats ●  
Non-operational floats ●

As of Nov 3, 2018



# FLOAT-BASED AIR-SEA CO<sub>2</sub> FLUX

$$F = k K_0 \Delta p\text{CO}_2$$

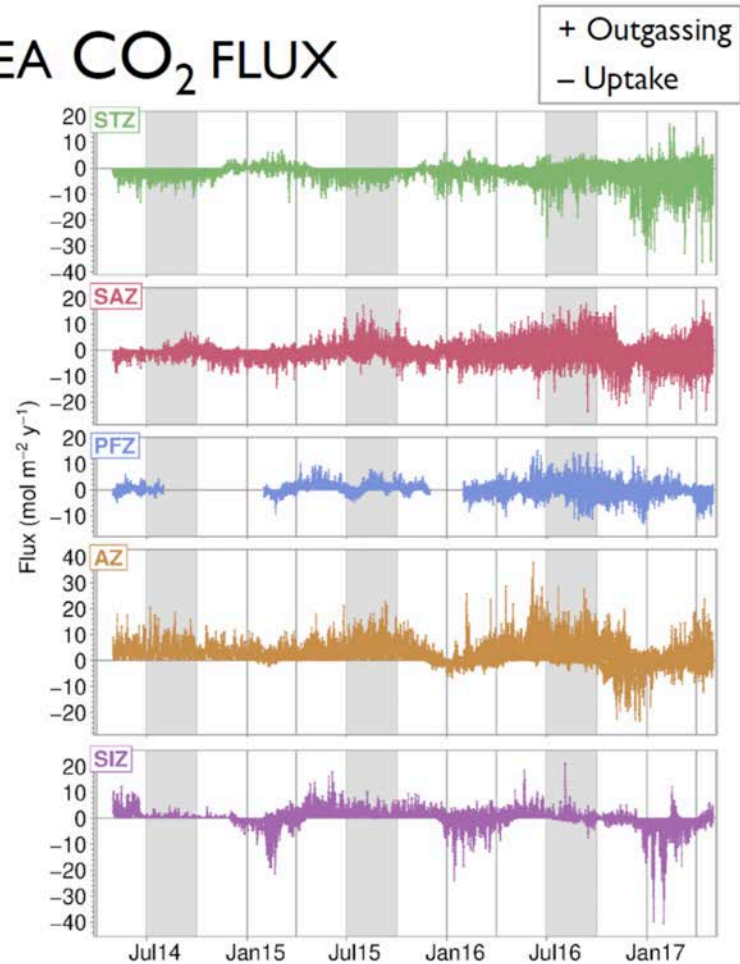
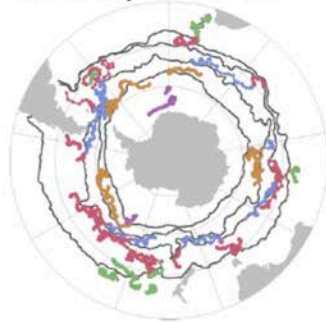
$$\Delta p\text{CO}_2 = p\text{CO}_2^{\text{ocn}} - p\text{CO}_2^{\text{atm}}$$

$p\text{CO}_2^{\text{atm}}$  from Cape Grim observations

Gas transfer velocity,  
 $\propto$  wind speed squared

$k$  Wanninkhof 2014  
 6-hourly ERA-Interim winds

$K_0$  solubility constant



Courtesy – A. Gray

# ANNUAL NET AIR-SEA CO<sub>2</sub> FLUX

+ Outgassing  
- Uptake

— Float estimate    - - - Tak09    ..... GCB17

Mean (mol m<sup>-2</sup> y<sup>-1</sup>)

**STZ: -1.3 ± 0.4**

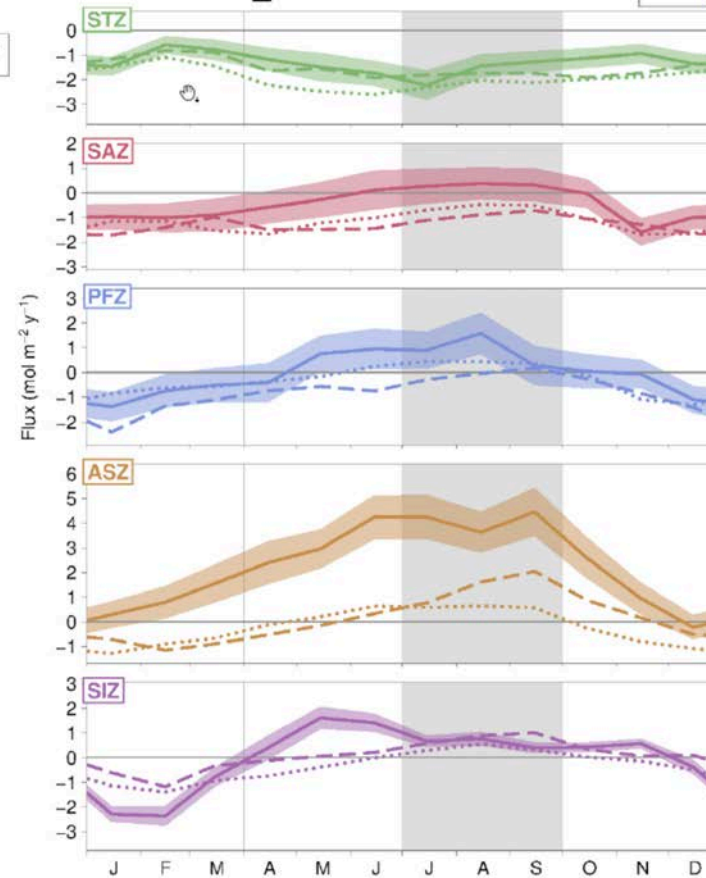
**SAZ: -0.4 ± 0.6**

**PFZ: 0.03 ± 0.7**

**ASZ: 2.3 ± 0.7**

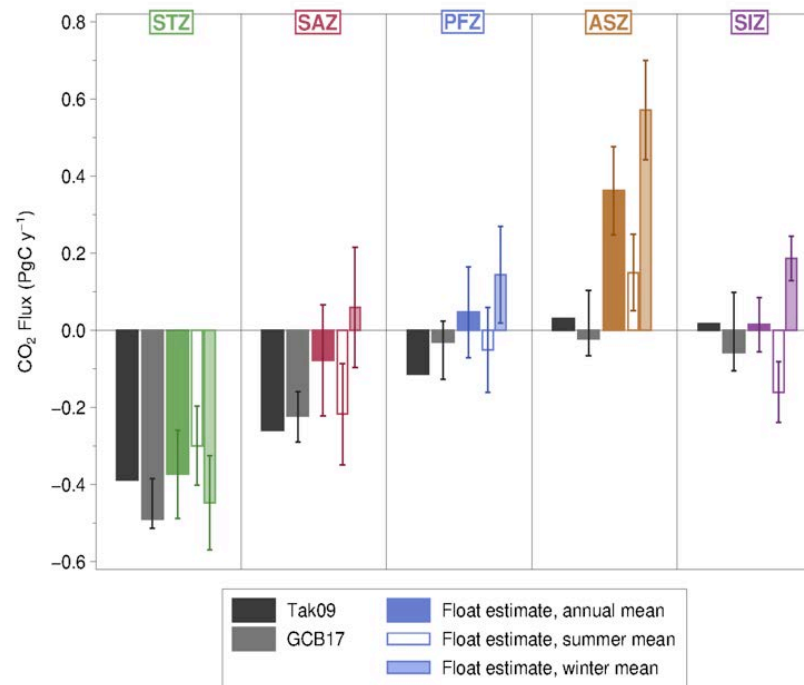
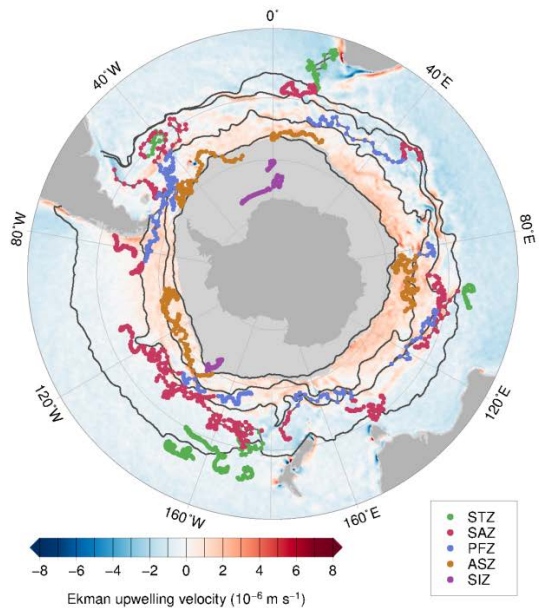
**SIZ: 0.04 ± 0.3**

Average global  
anthropogenic CO<sub>2</sub> uptake:  
-0.46 ± 0.14 mol m<sup>-2</sup> y<sup>-1</sup>




Courtesy – A. Gray


## Air-sea carbon flux from floats



In the high-latitude ASZ, monthly mean float-based fluxes diverge substantially from ship-based fluxes. The floats exhibit much stronger outgassing in the autumn and winter and much less uptake in the summer.



ADVANCING  
EARTH AND  
SPACE SCIENCE



### Geophysical Research Letters

---

**RESEARCH LETTER**  
10.1029/2018GL078013

**Key Points:**

- Measurements from biogeochemical profiling floats were used to estimate air-sea fluxes of carbon dioxide
- Significant annual net outgassing

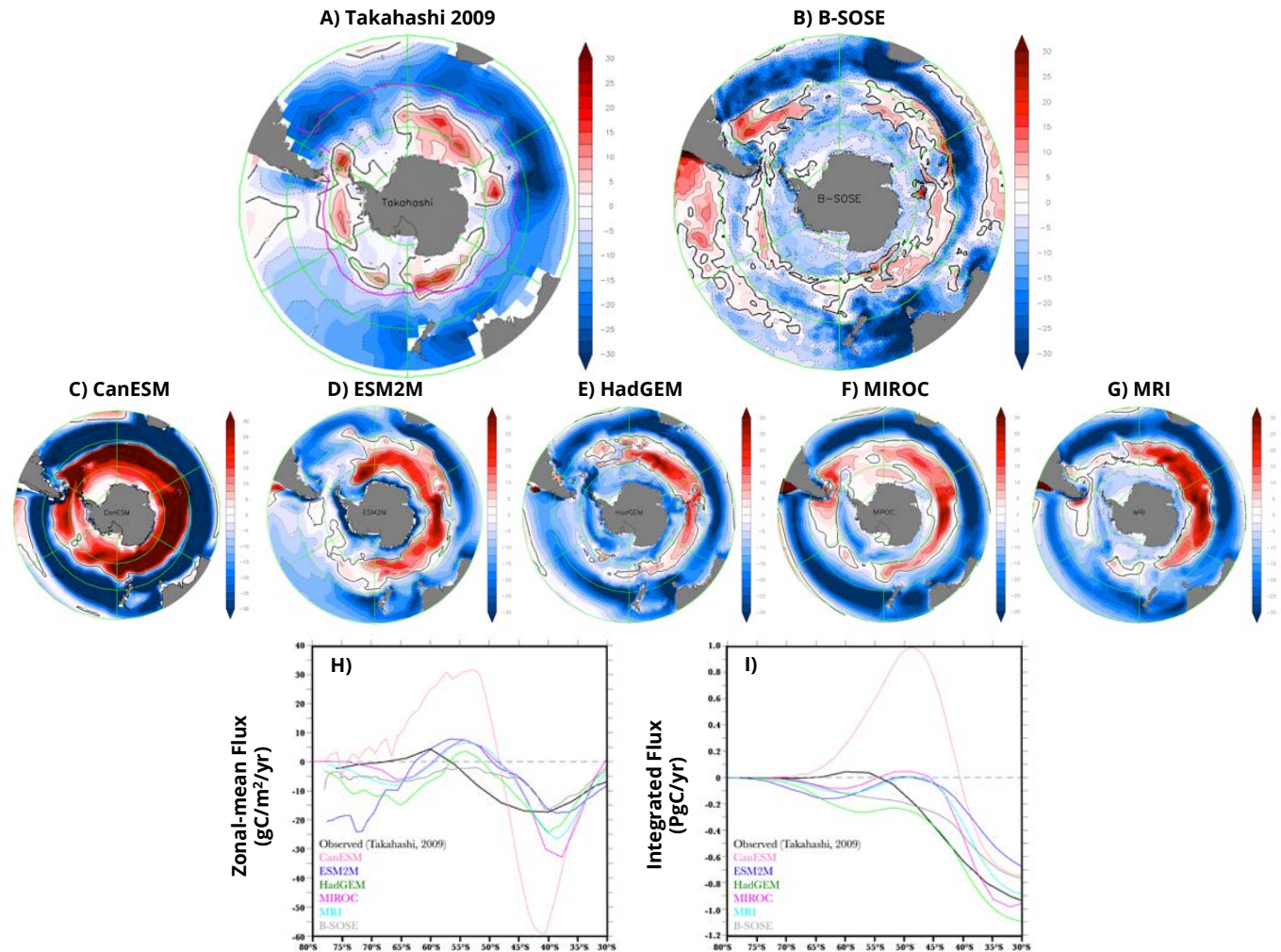
**Autonomous Biogeochemical Floats Detect Significant Carbon Dioxide Outgassing in the High-Latitude Southern Ocean**

Alison R. Gray<sup>1</sup>, Kenneth S. Johnson<sup>2</sup>, Seth M. Bushinsky<sup>3</sup>, Stephen C. Riser<sup>1</sup>, Joellen L. Russell<sup>4</sup>, Lynne D. Talley<sup>5</sup>, Rik Wanninkhof<sup>6</sup>, Nancy L. Williams<sup>7</sup>, and Jorge L. Sarmiento<sup>1</sup>

Courtesy – A. Gray

# Sea to Air CO<sub>2</sub> Flux (gC/m<sup>2</sup>/yr)

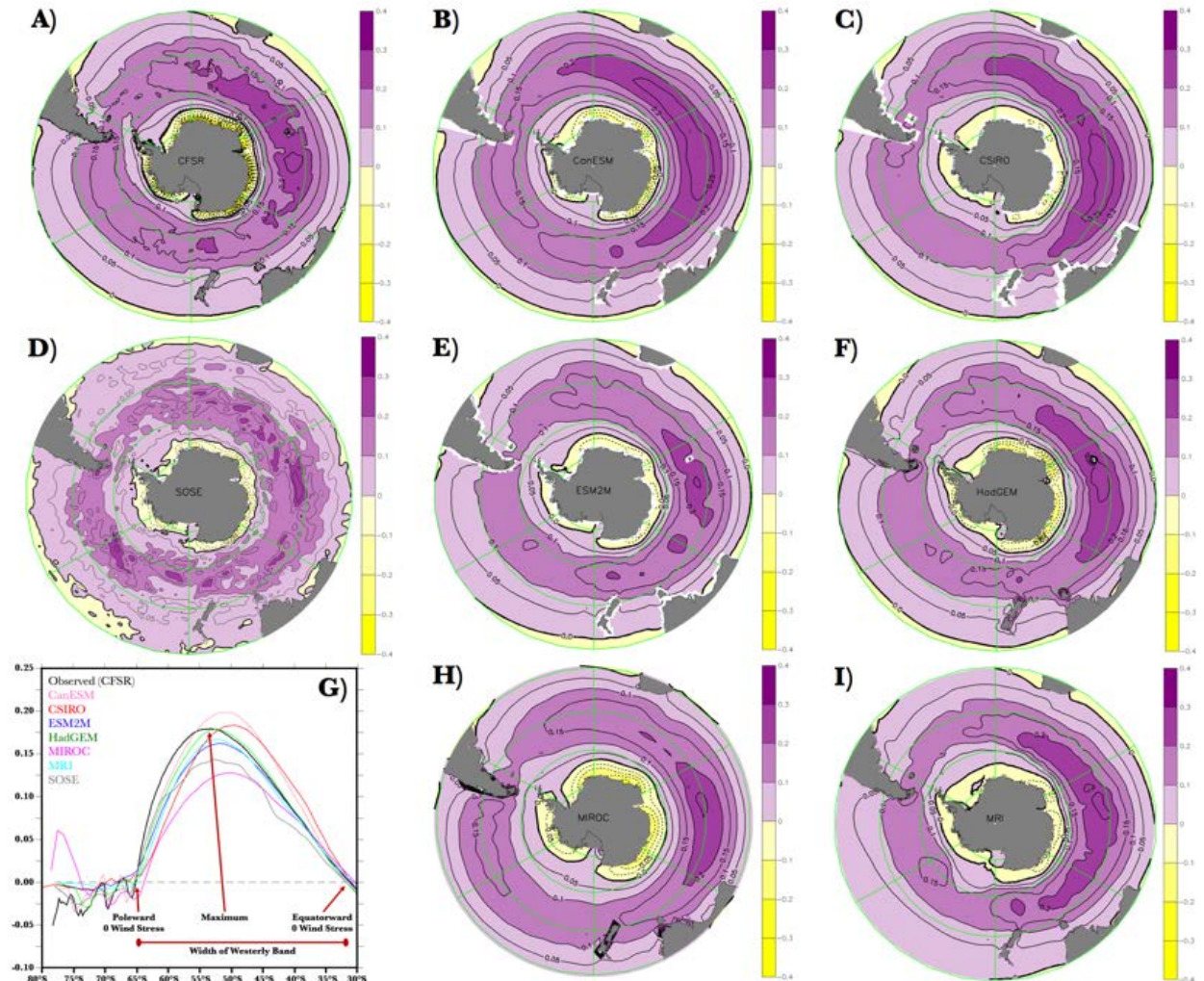
Red is outgassing,  
Blue is uptake



# Zonal Wind Stress (N/m<sup>2</sup>, Annual Mean)

Purple (positive) is  
clockwise (westerlies)

All the simulations have  
their strongest mean  
winds in the South  
Pacific sector (around  
Kerguelen), but each has  
its peak winds too far  
equatorward



# Metrics Paper



## Journal of Geophysical Research: Oceans

### RESEARCH ARTICLE

10.1002/2017JC013461

#### Special Section:

The Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) Project: Technologies, Methods, and Early Results

#### Key Points:

- Observationally based metrics are essential for assessing, comparing, and improving the heat and carbon cycles in climate simulations
- Metrics included here assess winds and heat and carbon uptake, ACC transport, sea ice extent, frontal positions, and pH
- Ocean heat and carbon uptake are strongly correlated in models and observations

## Metrics for the Evaluation of the Southern Ocean in Coupled Climate Models and Earth System Models

Joellen L. Russell<sup>1</sup> , Igor Kamenkovich<sup>2</sup> , Cecilia Bitz<sup>3</sup> , Raffaele Ferrari<sup>4</sup> , Sarah T. Gille<sup>5</sup> , Paul J. Goodman<sup>1</sup>, Robert Hallberg<sup>6</sup>, Kenneth Johnson<sup>7</sup> , Karina Khazmutdinova<sup>8</sup> , Irina Marinov<sup>9</sup>, Matthew Mazloff<sup>5</sup> , Stephen Riser<sup>10</sup>, Jorge L. Sarmiento<sup>11</sup> , Kevin Speer<sup>8</sup>, Lynne D. Talley<sup>5</sup> , and Rik Wanninkhof<sup>12</sup>

<sup>1</sup>Department of Geosciences, University of Arizona, Tucson, AZ, USA, <sup>2</sup>Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA, <sup>3</sup>Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA, <sup>4</sup>Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA, <sup>5</sup>Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA, <sup>6</sup>Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, NJ, USA, <sup>7</sup>Monterey Bay Aquarium Research Institute, Moss Landing, CA, USA, <sup>8</sup>Geophysical Fluid Dynamics Institute, Florida State University, Tallahassee, FL, USA, <sup>9</sup>Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, PA, USA, <sup>10</sup>School of Oceanography, University of Washington, Seattle, WA, USA, <sup>11</sup>Program in Atmospheric and Oceanic Sciences, Princeton University, Princeton, NJ, USA, <sup>12</sup>Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL, USA

#Great  
Antarctic  
Climate Hack



AntarcticClimate<sup>21</sup>

# WELCOME!

Ross ice shelf



SOCCOM



NASA images courtesy Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC



Goals: 1) Grow the community using observations to evaluate climate simulations  
2) Antarctic & SO metrics for ESMValTool

**#GreatAntarcticClimateHack** was held October 9-12, 2017 at the Scripps Institution of Oceanography Forum, La Jolla, CA. Our first-ever Climate Hack focused on bringing Antarctic and Southern Ocean observations to bear on evaluating the latest generation of climate and earth system models, to produce new climate model metrics for the 21<sup>st</sup> century.

The **#GreatAntarcticClimateHack** brought observational and simulation scientists together to use observational datasets to interrogate CMIP model results, thereby creating new model metrics and validation tools. The aim of the workshop was to facilitate preparation for the next IPCC report for a much broader science community, increase non-traditional climate modeling publications, and learn to apply/utilize data sets that help develop model validation skills.

<http://www.scar.org/antclim21/climatehack>

# Shared Metrics: ESMValTool



The Earth System Model eValuation Tool (ESMValTool) is a **community diagnostics and performance metrics tool for the evaluation of Earth System Models (ESMs)** that allows for routine comparison of single or multiple models, either against predecessor versions or against observations. Priority has been to focus on selected Essential Climate Variables, a range of known systematic biases common to ESMs, such as coupled tropical climate variability, monsoons, Southern Ocean processes, continental dry biases and soil hydrology-climate interactions, as well as atmospheric CO<sub>2</sub> budgets, tropospheric and stratospheric ozone, and tropospheric aerosols.

<https://www.esmvaltool.org/>



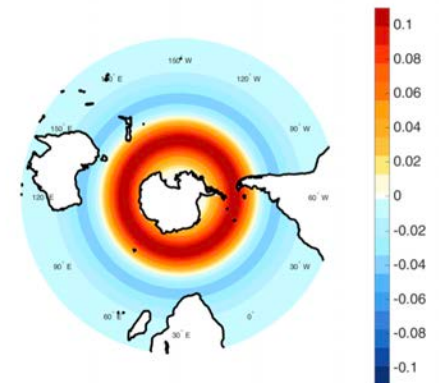
# SOMIP: The Global Warming Blindspot

3 EXPERIMENTS of 300 years (up to 900 if able) :

- **MELT:** An experiment where the stability of the Southern Ocean is changed via an external source of fresh water (so-called water hosing). Implications: 1 run (100-300 years).
- **WINDS:** An experiment that increases the winds over the Southern Ocean and shifts them poleward. Implications: 1 run (100-300 years).
- **BOTH:** An experiment that will use both the increased wind forcing and water hosing described above. Implications: 1 run (100-300 years).



Proposal: MELT & WIND perturbations



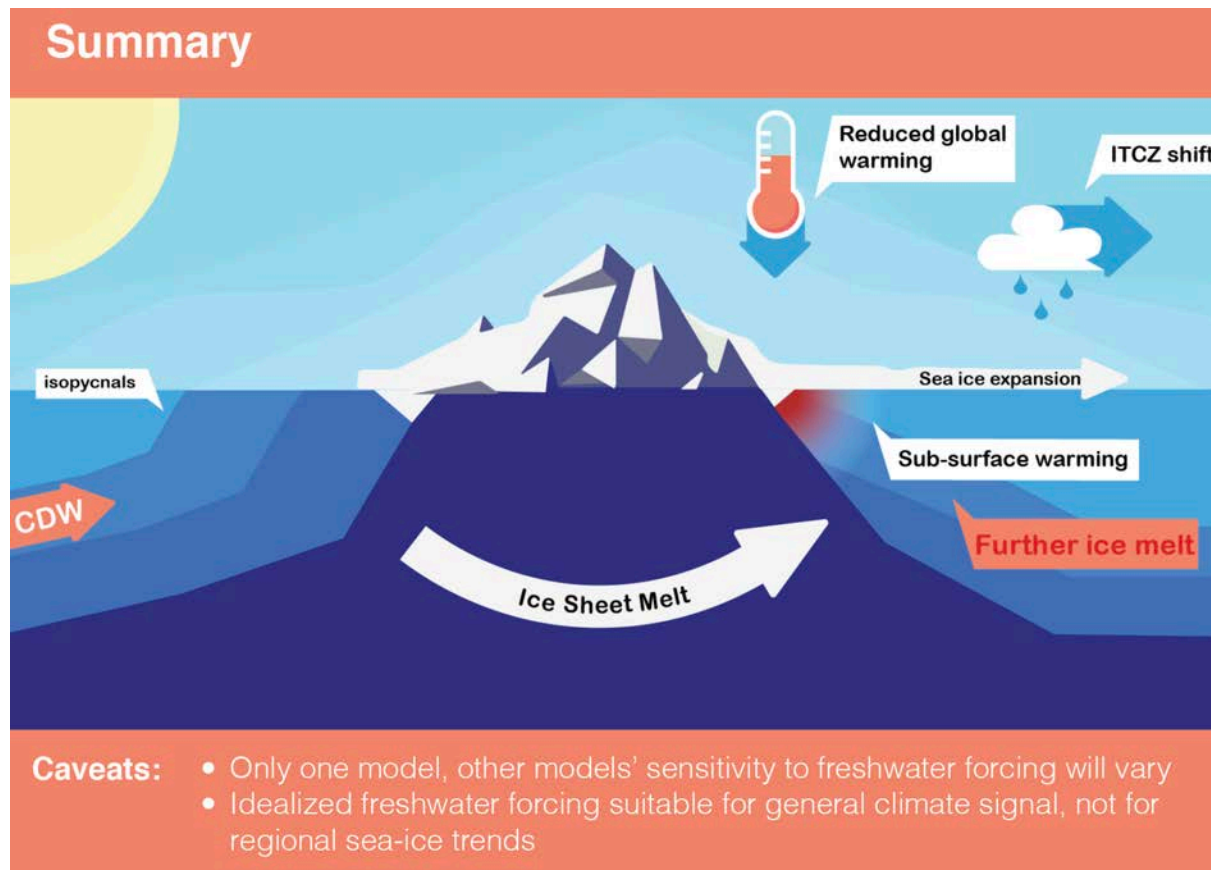


## Change in future climate due to Antarctic ice melt



**Ben Bronselaer**, Michael Winton, Stephen Griffies, Keith Rodgers, Bill Hurlin, Olga Sergienko, Ronald Stouffer and Joellen Russell

# Results from Melt experiments



- Extra melt reduces the global rate of warming; Date of 1.5°C warming delayed by ~15 years
- Sea ice area around Antarctica increases by 25% by ~2045
- Freshwater-induced warming at 400m increased by 4x; Ideally located to induce further basal melting via isopycnal transport

# Nations Unies Conférence sur les Changements Climatiques 2015

COP21/CMP11

Paris France



**#ParisAgreement**

**"Long live the planet.  
Long live Humanity. Long live life itself."**



Trust  
But Verify

# Two Methods for Estimating Emissions

## Bottom-Up

### UNFCCC National Inventories

- Estimates anthropogenic emissions and removals (sinks)
- Based on socio-economic statistics
- SELF-REPORTED

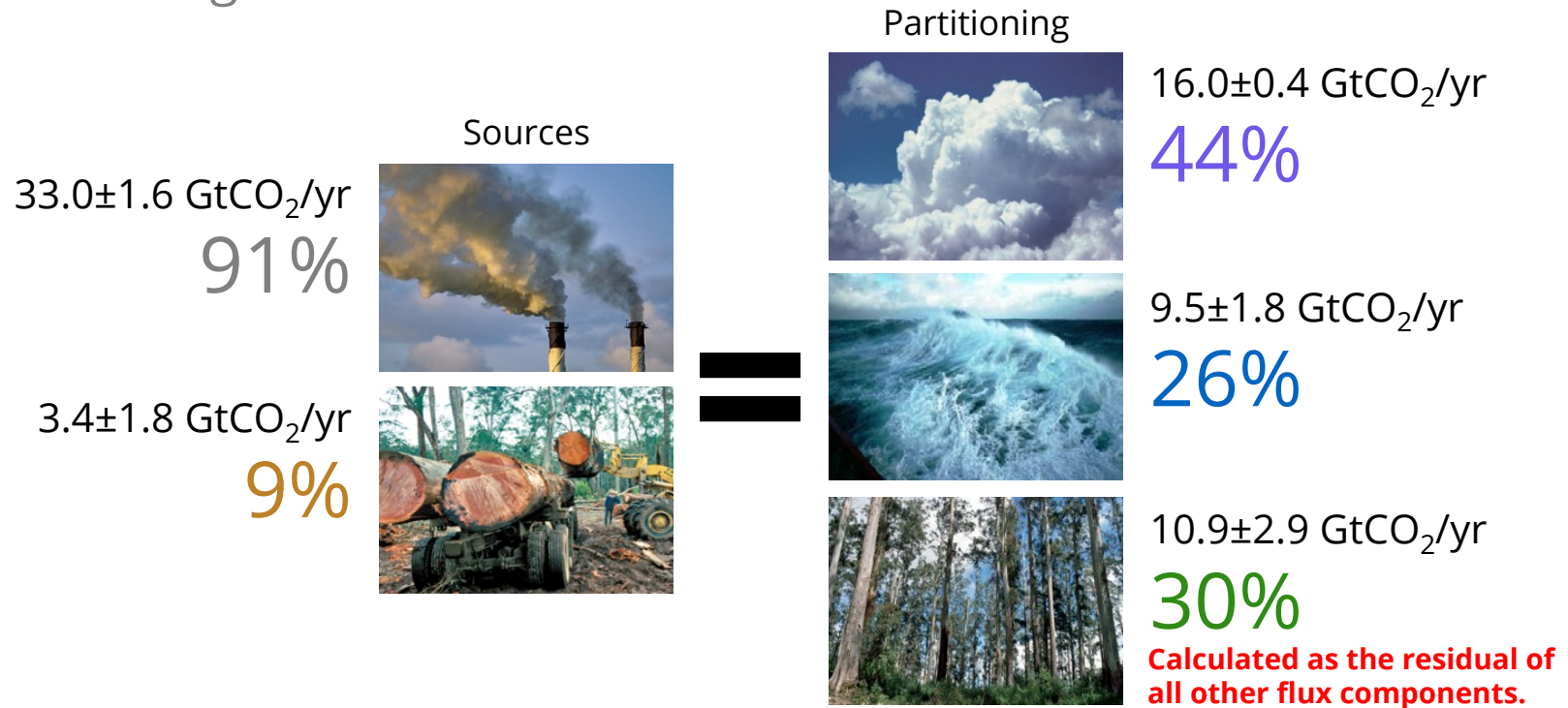
## Top-Down

### Tracer-transport Inversion

- Estimates net anthropogenic and natural sources and sinks
- Based on atmospheric and/or oceanic measurements of the gases and models of air and water flow

# Fate of Anthropogenic CO<sub>2</sub> Emissions

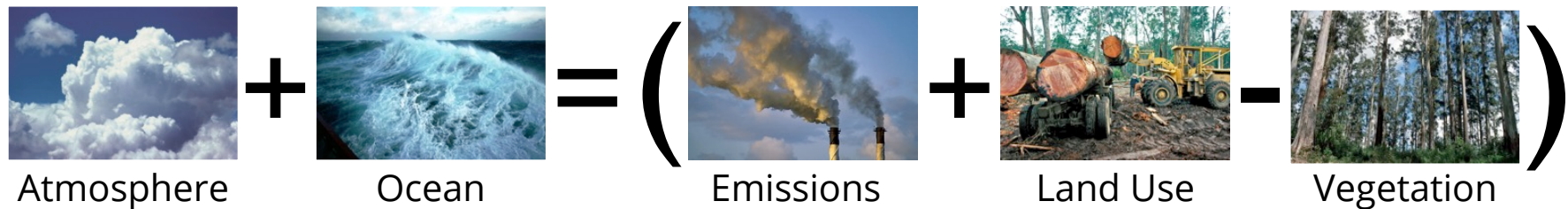
2005-14 average



Source: CDIAC; NOAA-ESRL; Houghton et al 2012; Giglio et al 2013; Le Quéré et al 2015; Global Carbon Budget 2015

# Atmosphere + Ocean = Land

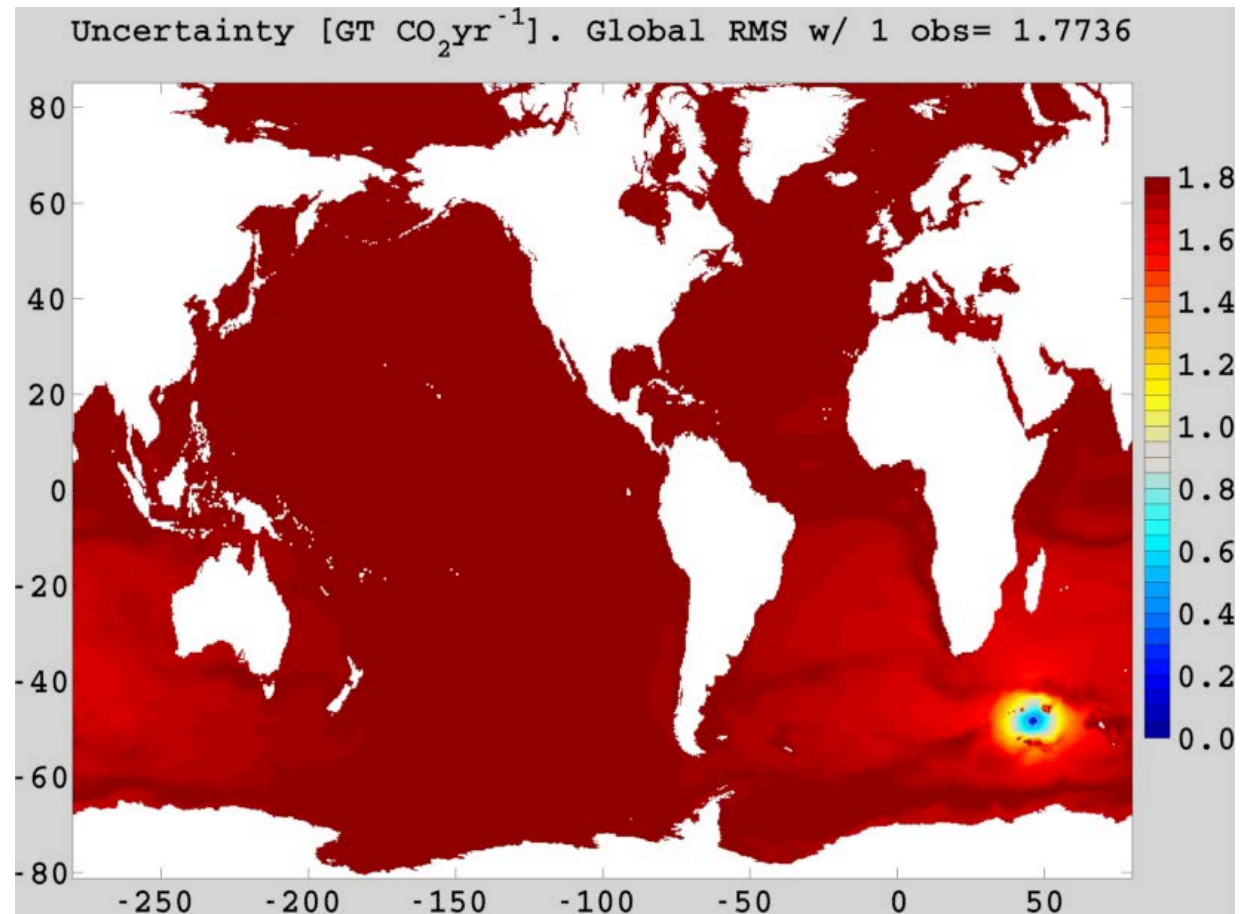
Where Land = (Emissions + Land Use Change - Vegetation)



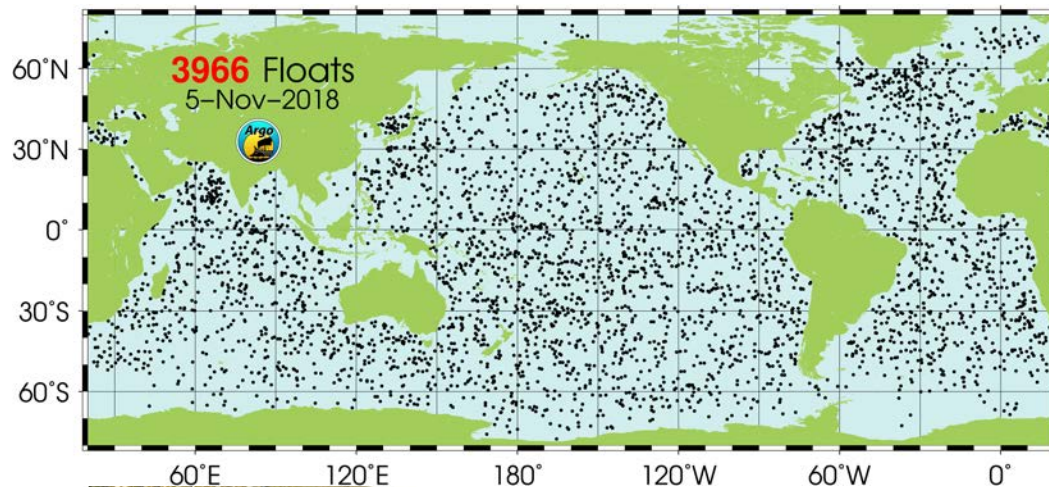
Reducing uncertainties in the ocean sink can reduce the total uncertainty in the global constraint on the carbon budget, particularly in the tropics

# Global Float Deployment

Color indicates relative uncertainty in space with respect to the locations of the floats (each blue bullseye is the location of a float).



[http://sose.ucsd.edu/DATA/OTHER/OSSE\\_run1.mov](http://sose.ucsd.edu/DATA/OTHER/OSSE_run1.mov)



Biogeochemical-Argo Network - Group photo

## Workshop on: Planning a Global BioGeoChemical-Argo Network

Villefranche-sur-Mer,  
11-13 January 2016

Draft implementation plan  
published



Courtesy – K. Johnson

# What do we get from a Global BGC-Argo Array?

A transformative shift from reactive to **proactive** management of marine resources and an expansion of the Blue Economy

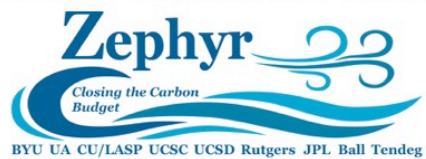
- a) We observe the current state of the ocean's productivity and health
- b) We use data assimilation to produce a 4-D real-time estimate of the physical, chemical and biological conditions supporting marine productivity and marine ecosystems
- c) We contribute to the improvement of short-term predictions and long-term projections, and these data can be immediately transferred to marine resource managers, scientists, and the public

# Successes of SOCCOM

- a) The successful deployment, calibration and real-time data management of the SOCCOM BGC float array in the Southern Ocean should be considered as a successful, large pilot program for the global array
- b) The successful assimilation of BGC parameters into the state estimate (B-SOSE) demonstrates that we can assess marine resources and marine productivity in near real time
- c) Successful use of SOCCOM data w/ Earth System Model simulations has already identified new feedbacks in the climate system and has led to a reduction in the uncertainty associated with short-term predictions and longer-term projections

# Ready to deploy BGC-Argo globally

- a) BGC-sensored Argo floats are available commercially
- b) Floats are now proven successful for the long-term deployments necessary to create a global array, and real-time public data availability as part of Argo data management is in place
- c) Global BGC data are needed for assimilation into state estimates to provide fisheries and ecosystem managers around the world the information they need to adjust fishing levels and locations, conserve habitats, and reduce threats in time to make a difference as the ocean changes, both from natural variation and from climate change



Volume I Technical



Proposal Number: NNH17ZDA004O -EV15

Proposal to:  
Customer  
Address  
Attn:

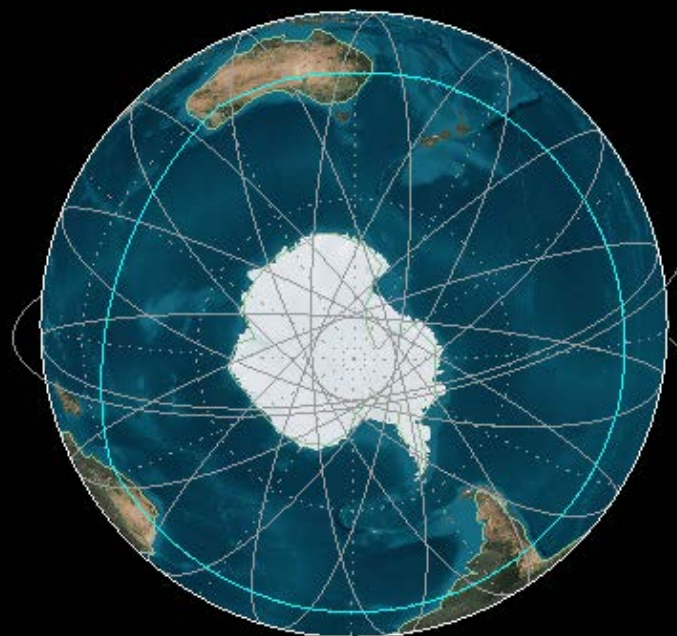
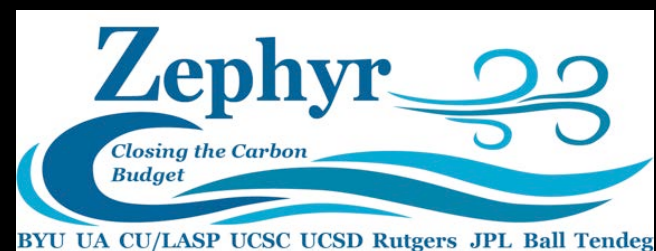
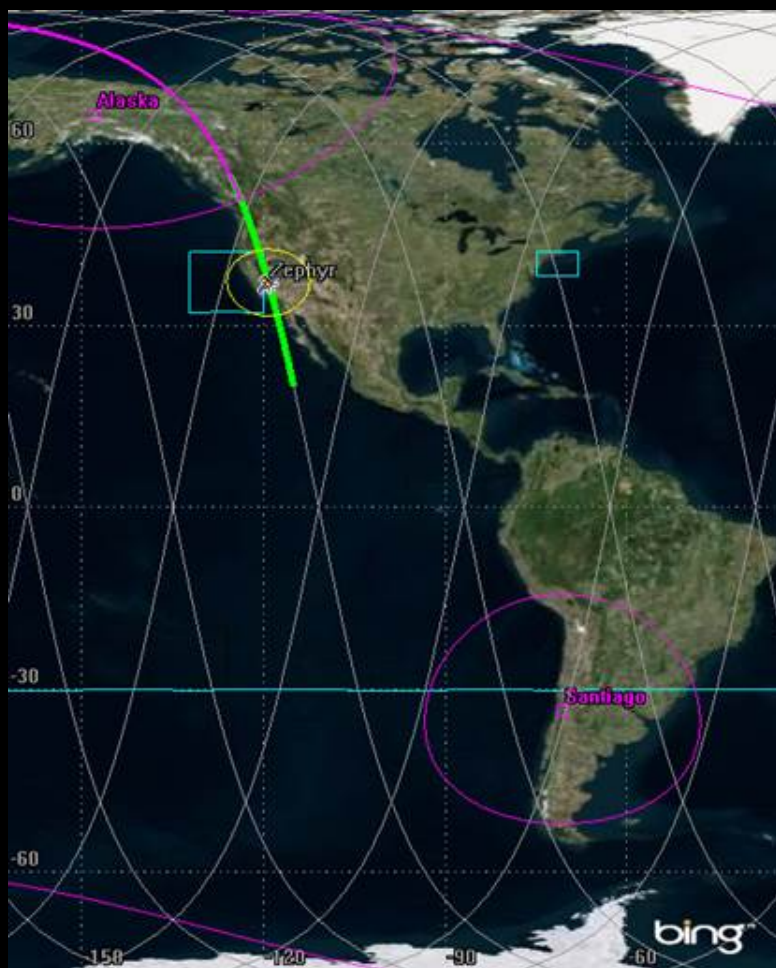
Proposal from:  
Science Team  
Address

October xx, 2018



Proprietary Statement

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed diam nonummy nibh euismod tincidunt ut laoreet dolore magna aliquam erat volutpat. Ut  
visi enim ad minim veniam, quis nostrud exerci tation ullamcorper suscipit lobortis nisl ut aliquip ex ea commodo consequat. Duis autem vel eum iriure  
dolor in hendrerit in vulputate velit esse molestie consequat, vel illum dolore eu feugiat nulla facilisis at vero eros et accumsan et justo odio dignissim qui  
blandit praesent luptatum zzril delenit augue duiis dolore feugait nulla facilisi.



## B Fact Sheet



BYU UA CU/LASP UCSC UCSD Rutgers JPL Ball Tende

A Process-Study Investigation to Quantify Coastal Oceanic Carbon Flux using Surface Vector Wind Fields and High Resolution Models

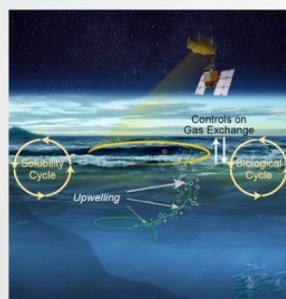
PI: Dr. David Long, BYU  
DPI: Dr. Joellen Russell, UA

### Investigation Overview

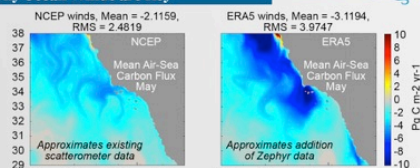
Zephyr is a small, low-cost scatterometer suitable for flight on a SmallSat. An innovative use of a well-proven technique, Zephyr will produce groundbreaking wind vector datasets over critical coastal areas at unprecedented temporal and spatial resolutions.

The team is led by PI Dr. David Long, BYU, who for over 30 years has been at the forefront of scatterometry system engineering and science, from NASA's QuikSCAT to ESA's ASCAT.

He is joined by Dr. Joellen Russell, UA, a leader in Earth System Modeling and a science team focused on assimilating Zephyr data into high resolution models to quantitatively assess coastal air-sea carbon exchange.



### Why Ocean Winds are Key



Preliminary OSSEs of carbon flux state estimates for the California Current Region suggest that adding the high spatial and temporal resolution Zephyr wind data to the models significantly improves their ability to capture the real amplitude and variability (not shown) of air-sea carbon flux in coastal domains.

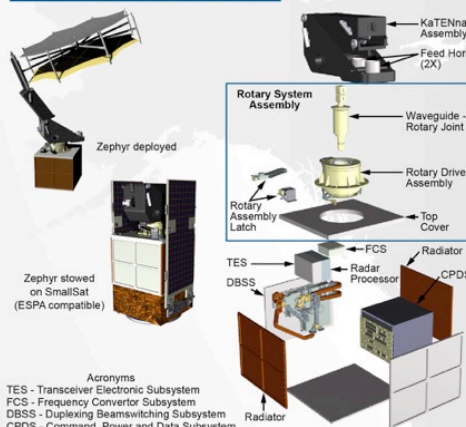
### Science Objectives

- Use Zephyr high spatial and temporal surface vector wind measurements to improve computations of air-sea carbon flux in the coastal ocean
- Improve coastal ocean carbon flux estimates in data assimilative dynamical-BGC model calculations for selected coastal ocean domains, as well as in a coarser resolution global "data assimilative dynamical-BGC model", using carbon fluxes generated from Objective 1
- Combine high resolution coastal assimilations from Objective 2 with global 1/3° assimilations to construct a global carbon flux state estimate

### Significance to NASA

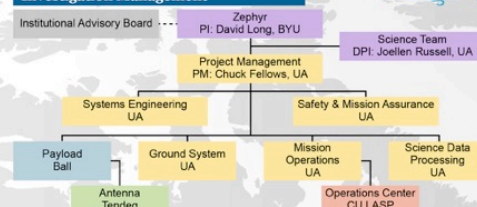
- First high-resolution, coastal zone investigation to study the interaction between **carbon exchange** and ocean surface winds
- Specifically addresses key questions from the 2017 ESAS, including
  - Ecosystem Change (E-3): What are the fluxes of **carbon**, water, nutrients, and energy within ecosystems, and how and why are they changing
  - Climate (C-4a): Improve the estimates of global air-sea fluxes of heat, momentum, water vapor and other gases, like **carbon** and methane
- Fulfills critical parts of the **Aquatic Biogeochemistry and Ocean Surface Winds and Currents Targeted Observables**

### Instrument & Key Characteristics



Accommodation Parameter	Value	Instrument Parameter	Value
Orbit altitude	550 km ±50 km	Ground resolution (processed data)	2.5 km
Orbit inclination	Sun-synch	Antenna spin rate	18 RPM
Orbit ascending node time	3:00 pm ±1 hr	Swath width	1200 km
Instrument mass	65.5 kg	Frequency	13.4 ±0.05 GHz
Instrument orbit	98.5 W (science orbit)	Transmit power (at antenna)	≈32 W
average power	61.0 W (non-operating orbit)	Beam angles	42° and 48° off-nadir
Instrument Stowed	0.45 x 0.49 x 0.71 m	Chirp bandwidth	250 kHz
Instrument volume	Deployed: 1.35 x 1.29 x 1.84 m	Pulse repetition frequency	187 Hz
Instrument peak data rate	52 kbps	Pulse length	1.5 msec
Pointing control required	0.1 deg, 1σ	On-orbit calibration	Loopback and noise (gain and Tx power on the ground)
Pointing knowledge req'd	0.025 deg, 1σ		

### Investigation Management



### Participating Organizations

Investigation Management and Instrument Development	Science, Data, and Applications
BYU PI Institution, Mission and Investigation Leadership, Instrument Science and Calibration, L1 - L3 Science Data Processing	UA Deputy PI and Science Team Leadership, Earth System Model (ESM) Evaluation, Applications POC, L4 Products
UCSC Project Management, Systems Engineering, S&MA, Data Archive and Distribution	UCSC BioGeoChemical (BGC) Flux Calculation and Analyses in the California Current System (CCS)
UCSD Flight Instrument Development, AI&T, Sustaining Engineering Instrument Science	UCSD Regional and Global Data Assimilation and State Estimation
Rutgers Deployable Antenna, Development and AI&T	Rutgers BioGeoChemical (BGC) Flux Calculations and Analyses in the Middle Atlantic Bight (MAB)
CU Mission and Instrument Operations Center	CU Instrument Science, Carbon Flux Calculations and Analyses in the Antarctic Circumpolar Current (ACC)
JPL Mission and Instrument Operations Center	JPL Calibration and Validation Lead

### Science Team

David Long, PI	BYU	Oscar Schofield, Co-I	Rutgers
Joellen Russell, DPI	UA	Enrique Curchiser, Co-I	Rutgers
Paul Goodman, Co-I	UA	Scott Glenn, Co-I	Rutgers
Matthias Morfeld, Co-I	UA	Javier Zavala-Garay Co-I	Rutgers
Andrew Moore, Co-I	UCSC	Ralph Milliff, Co-I	CU
Chris Edwards, Co-I	UCSC	Nicole Lovenduski, Co-I	CU
Jerome Fletcher, Co-I	UCSC	Manoja Weiss, Liaison	Ball
Matthew Madorff, Co-I	UCSD/SIO	Quinn Remund, Liaison	Ball
Ernesto Rodriguez, Co-I	JPL		

### Schedule & Cost Summary

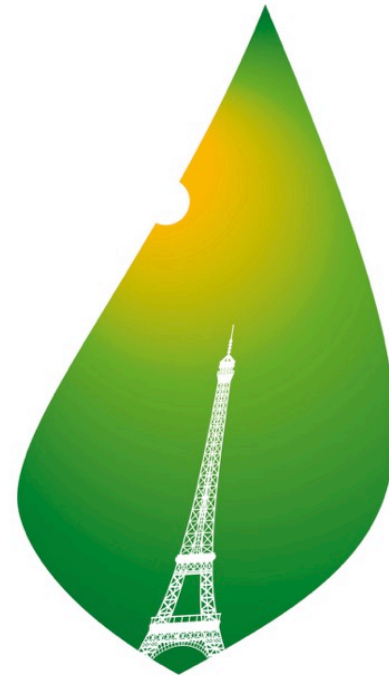
CY19	20	21	22	23	24	25	26	27
KDP-B	KDP-C		KDP-D		KDP-E		KDP-F	
ATP	SRR	PDR	CDR	SIR	PSR	FRR	ORR	Launch
								Investigation
								Completes
RY	PI Mission Cost	3,818	18,957	63,855	9,806	10,005	964	\$107,404
	Reserve, %	8	16	33	25	10	5	25.4%
	Total Mission Cost	3,849	19,108	64,448	10,536	11,125	989	\$115,055
FY22	PI Mission Cost	4,051	19,932	64,819	9,313	9,041	825	\$107,981
	Reserve, %	8	16	33	25	10	5	25.4%
	Total Mission Cost	4,083	20,091	65,414	10,595	10,054	846	\$115,164

# We need global carbon “weather”

Ten years ago we didn't have:

- An international political agreement to address the carbon cycle (COP21)
- Carbon-observing satellite (OCO-2)
- Earth System Models (CMIP5)
- Biogeochemical-Argo floats (SOCCOM)

Now we have all the pieces!



COP21 • CMP11  
**PARIS 2015**  
UN CLIMATE CHANGE CONFERENCE

A photograph of Earth from space, showing the horizon and clouds. The sun is visible in the upper center, creating a lens flare effect. The text "What comes next?" is overlaid in white.

# What comes next?

Build out global array of BGC-Argo floats.  
Get Zephyr up to calculate "carbon weather".  
Send the top 10 economies their monthly carbon "bill"  
Save the planet (or at least the humans)!